



Performance of Small Bore 60NiTi Hybrid Ball Bearings: Preliminary Life Test Results

Dr. Christopher DellaCorte
and

Dr. S. Adam Howard
NASA, Glenn Research Center
Cleveland, Ohio

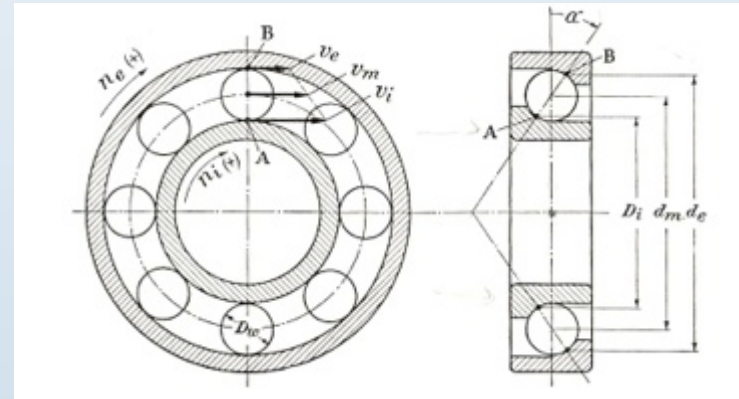
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Materials Requirements: NASA sets the bar high

(Space challenges conventional technology)

- **Attributes sought:**
 - Hard (Rockwell C58 or better)
 - Wear-resistant and compatible with existing lubricants
 - Resistant to rolling contact fatigue (RCF)
 - Fracture resistant
 - Corrosion resistant (preferably immune)
 - Low density (to reduce centrifugal loads at high rpm)
 - Capable of producing ultra-smooth surface finishes
 - Dimensionally stable and easy to manufacture





Bearing Material: State-of-the-Art (SOA)

(Current suite of candidates is severely limited)

- **Four general types of bearing materials:**
 - Steels (Corrosion resistant steels, martensitic, austenitic)
 - Ceramics (Si_3N_4 balls + steel races, a.k.a., hybrid bearings)
 - Superalloys (e.g., jet turbine blade alloys)
 - Non-ferrous alloys (bronze, nylon etc.)
- **Each of these has inherent shortcomings:**
 - Hard steels are prone to rusting (even “stainless steels” like 440C)
 - Superalloys and austenitic stainless steels (304ss) are soft.
 - Ceramics have thermal expansion mismatch and dent steel races
 - Non-Ferrous materials are weak and lack temperature capabilities
- **No known bearing material blends all the desired attributes:**
 - High hardness, corrosion immunity, toughness, surface finish, electrical conductivity, non-magnetic, manufacturability, etc.



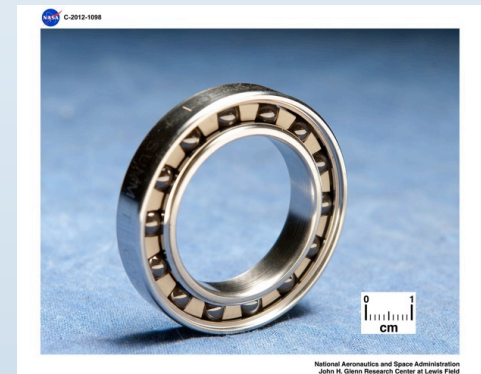
Superelastic Bearings: NiTi based intermetallics

(Hard but resilient material related to shape memory alloys)

- **60NiTi Basics: market name NiTiNOL 60**
 - W.J. Buehler invented NiTiNOL in the 1950's. Acronym for Ni-Ti-Naval-Ordnance-Laboratory.
 - 60NiTi (60 wt% Ni) is the baseline composition. Alloying with Hf, Zr, and Ta improves microstructure and processing.
 - 60NiTi is not a metal or a ceramic: a weakly ordered inter-metallic compound.
 - Closely related to the shape memory alloys, like NiTiNOL 55, but dimensionally stable.
 - 60NiTi is bearing hard (Rockwell C60) but only half as stiff as steel.
 - Brinell damage threshold load (pounds, kg_f) is significantly (3-5X) higher than steel.



Highly polished 60NiTi bearing balls



60NiTi-Si₃N₄ Hybrid Bearing



Technical Properties Comparison:

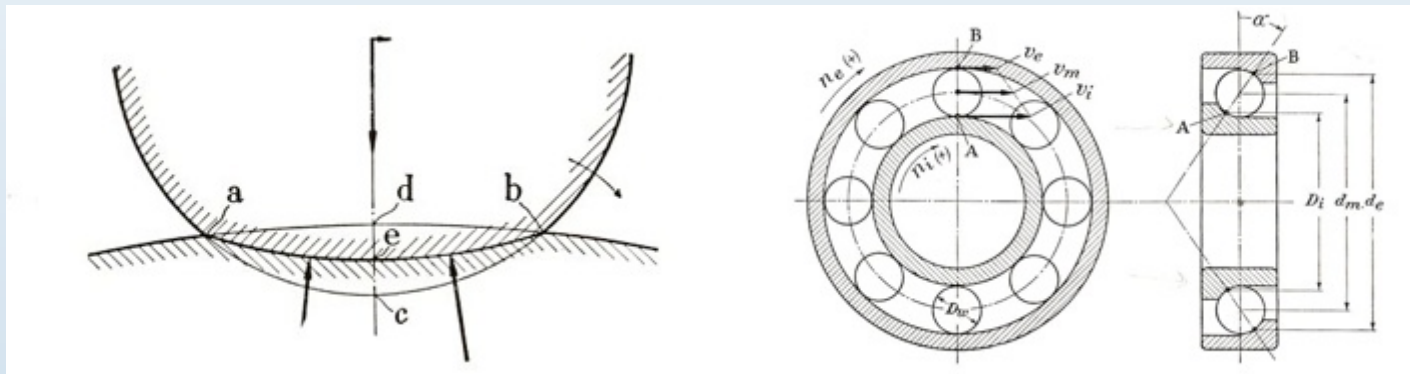
Property	60NiTi	440C	Si ₃ N ₄	M-50
Density	6.7 g/cc	7.7 g/cc	3.2 g/cc	8.0 g/cc
Hardness	56 to 62 HRC	58 to 62 HRC	1300 to 1500 Hv	60 to 65 HRC
Thermal conductivity W/m-°K	~9 to 14	24	33	~36
Thermal expansion	~11.2×10 ⁻⁶ /°C	10×10 ⁻⁶ /°C	2.6×10 ⁻⁶ /°C	~11×10 ⁻⁶ /°C
Magnetic	Non	Magnetic	Non	Magnetic
Corrosion resistance	Excellent (Aqueous and acidic)	Marginal	Excellent	Poor
Tensile/(Flexural strength)	~1000(1500) MPa	1900 MPa	(600 to 1200) MPa	2500 MPa
Young's Modulus	~95 GPa	200 GPa	310 GPa	210 GPa
Poisson's ratio	~0.34	0.3	0.27	0.30
Fracture toughness	~20 MPa/√m	22 MPa/√m	5 to 7 MPa/√m	20 to 23 MPa/√m
Maximum use temp	~400 °C	~400 °C	~1100 °C	~400 °C
Electrical resistivity	~1.04×10 ⁻⁶ Ω-m	~0.60×10 ⁻⁶ Ω-m	Insulator	~0.18×10 ⁻⁶ Ω-m

- ***Modulus is ½ that of steel, yet hardness is comparable.***
- ***Tensile strength akin to ceramics.***
- ***Does not rust.***



60NiTi: Low Modulus yet Hard?

- **60NiTi Superelastic: surprising and welcome behavior:**
 - Reduced stiffness (modulus) produces more deformation, higher contact area, lower stress
 - It is contrary to a century of experience with hard bearing materials!
 - High hardness combines with low stiffness to improve dent resistance.
 - Brinell denting test can quantify resilience effect.



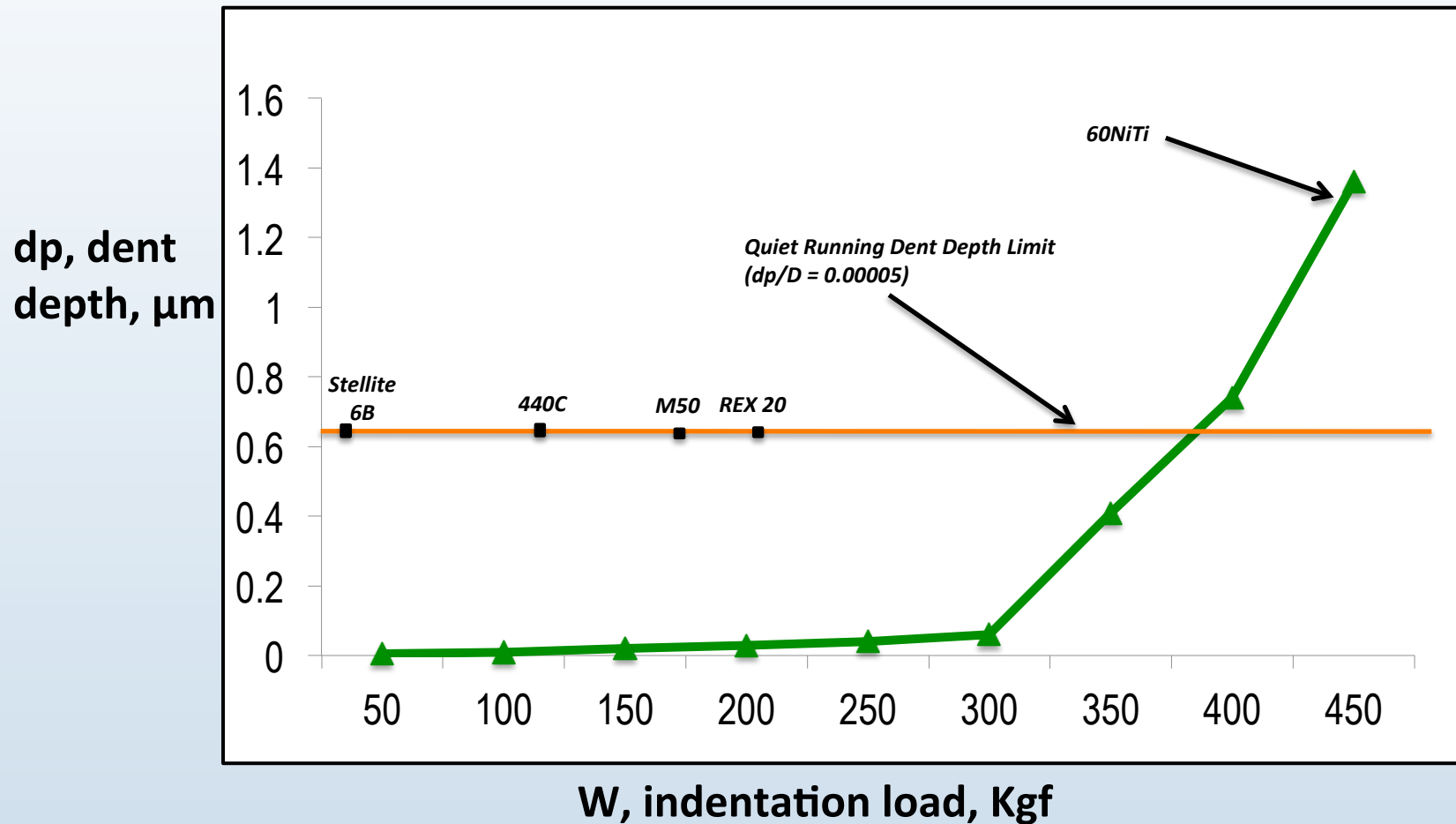
Balls touch races at small points causing race surface dents

Dents on race surface cause rough running and premature failure



Dent Depth vs. Load

(12.7 mm diameter Si_3N_4 ball against 60NiTi plate)

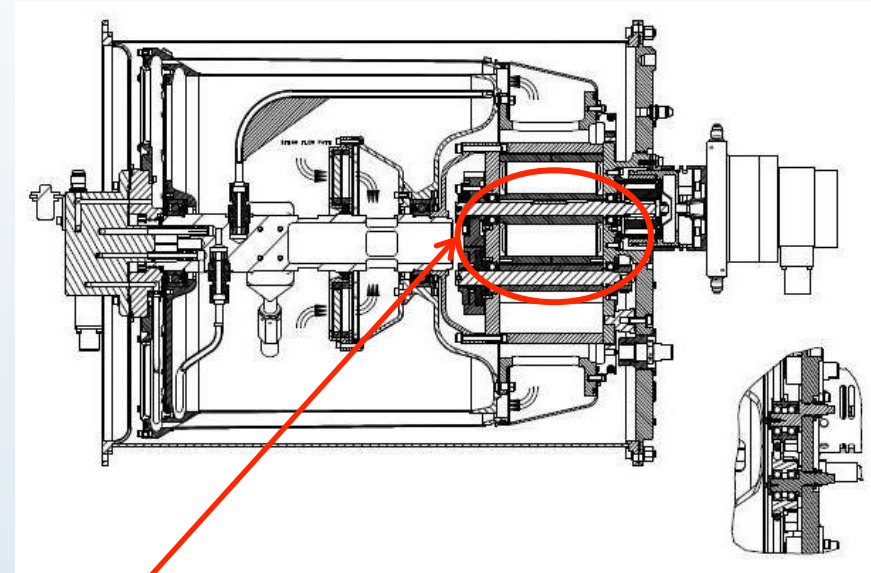




Opportunities: Superelastic Bearings

(ISS Wastewater purifier system offers technology “pull”)

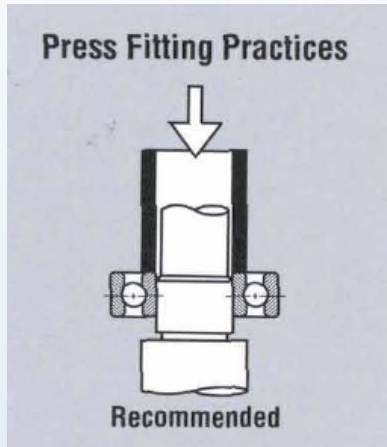
- **Superelastics enabling characteristics:**
 - Impact load tolerance.
 - Intrinsic corrosion resistance (cannot rust)
 - High static load capability.
 - Non-magnetic but electrically conductive
 - Emerging manufacturing (M&P) database.
- **ISS Urine Processor Pathfinder applications:**
 - 50mm bore centrifuge bearings (wet, low speed, low load).
 - Compressor drive gears (dry lubed, damp, low load, high speed).
 - 12.7mm compressor bearings (moderate load, high speed, inaccessible location).



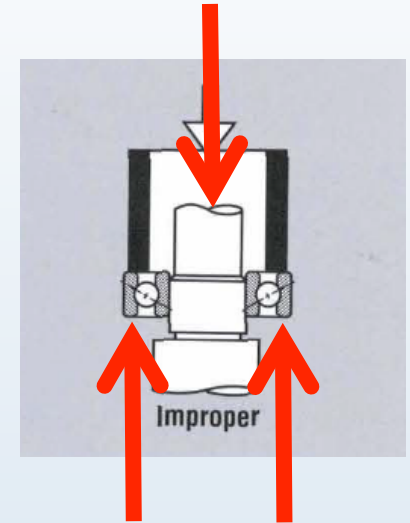
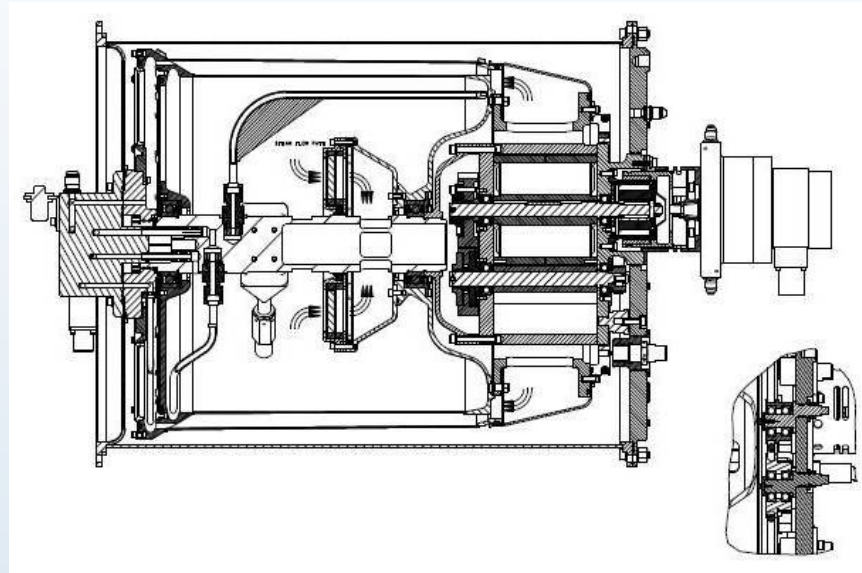
- **Compressor Bearings**
 - *Support roots blower lobes.*
 - *2000 rpm, high precision.*
 - *Moisture exposure.*
 - *Accessible for installation*
 - *Disassembly loads ball-race contact requiring bearing replacement.*



Current Machine Design: Assembly: OK, Removal: Not OK



Acceptable

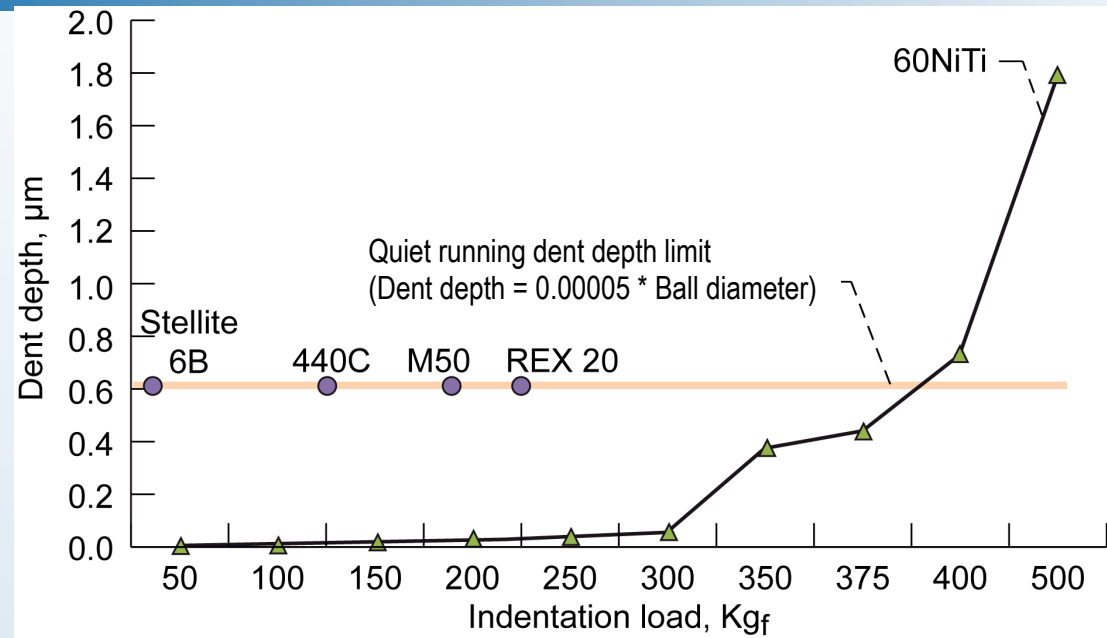
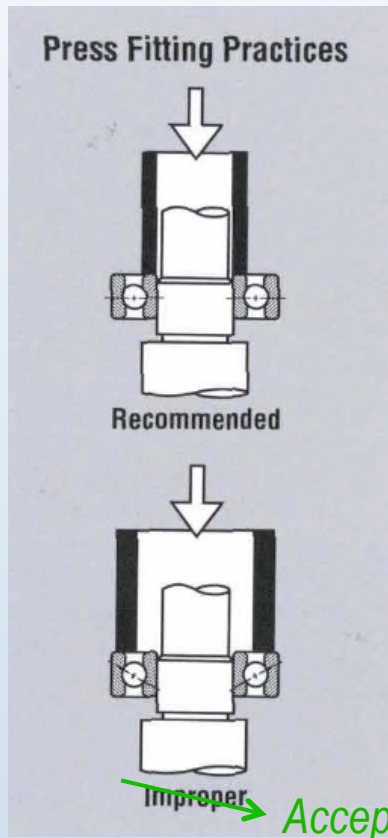


Unacceptable

- **Current Bearing: Deep Groove Instrument Design**
 - Installation accomplished by pressing on both rings against tight fits.
 - Disassembly achieved by pulling on housings resulting in scrapped bearings.



Superelastic Bearing: Taking Advantage of NiTi Characteristics.



- 60NiTi has more load capability for given geometry:
 - Calculations, computer modeling and subsequent experiments led to a 60NiTi-hybrid bearing that withstands removal forces.
 - Does the bearing perform (life)?



Design Approach: Reusable NiTi R8 Compressor Bearing

(Leverage geometry and materials)

- **Materials**

- 60NiTi has static stress limit of 3.1GPa. ~3x the static load capacity of steel.
- Si_3N_4 balls match current baseline but reduce load capacity.

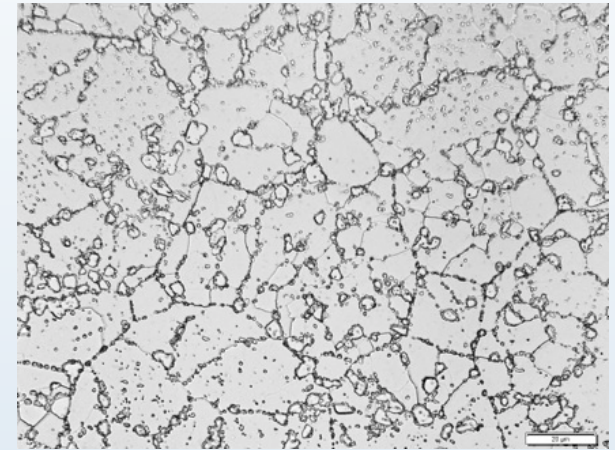
- **Operating Conditions**

- Moderate speed (2000 rpm), low operating load.
- Moisture exposure, 5000 hour life requirement.
- 1.5-2.2kN installation/removal axial load.

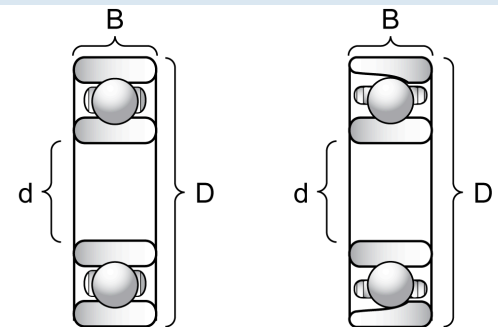
- **Bearing Geometry**

- Baseline bearing is deep groove ball bearing with conventional internal geometry.

60NiTi-Microstructure
(etched to reveal grains)



Ball-Race Contact Engineering





Removable Superelastic Bearings: Detailed Design (ADORE bearing analysis)

- The resulting modified bearing was manufactured by combination of in-house and specialty bearing firm.





Compressor Bearing Rig

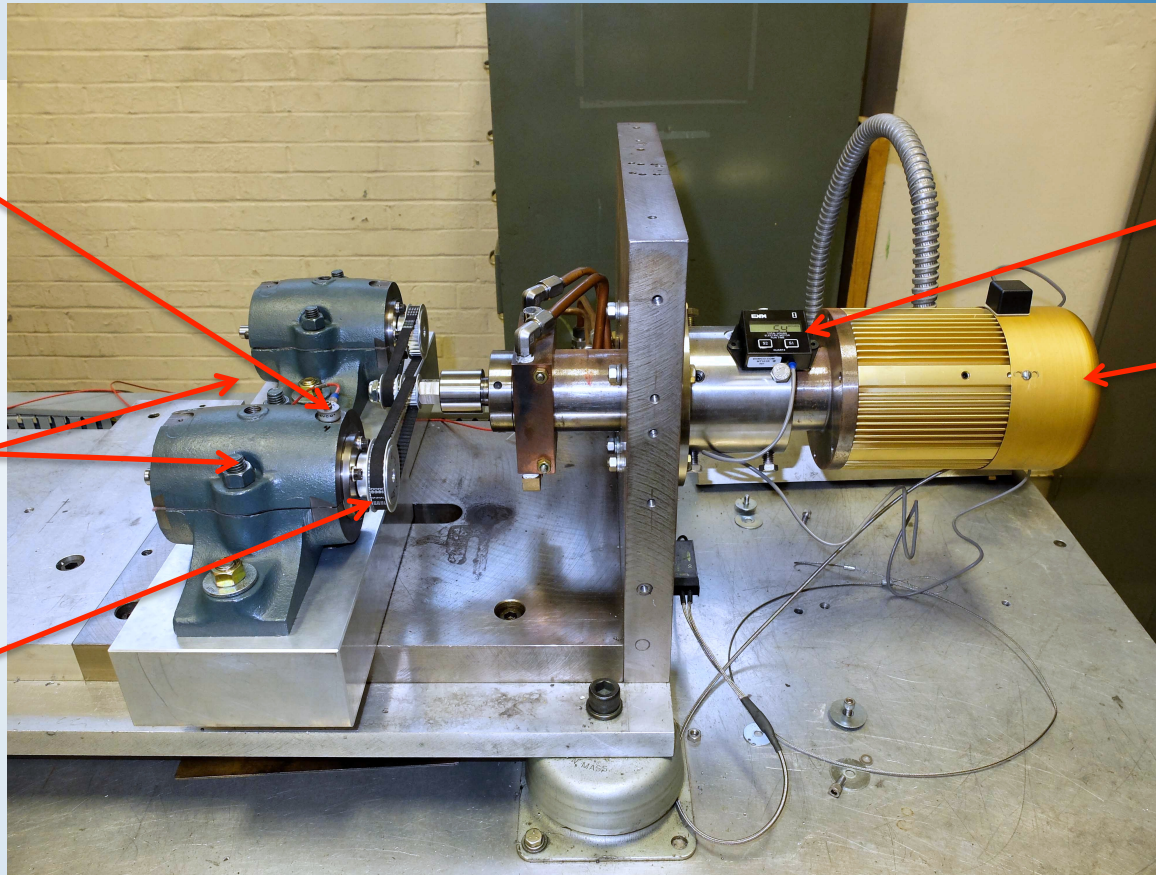
Vibe
Accelerometers
(4)

Test Bearing
Spindles

Toothed Belt Driven

Hour Meter

Drive Motor



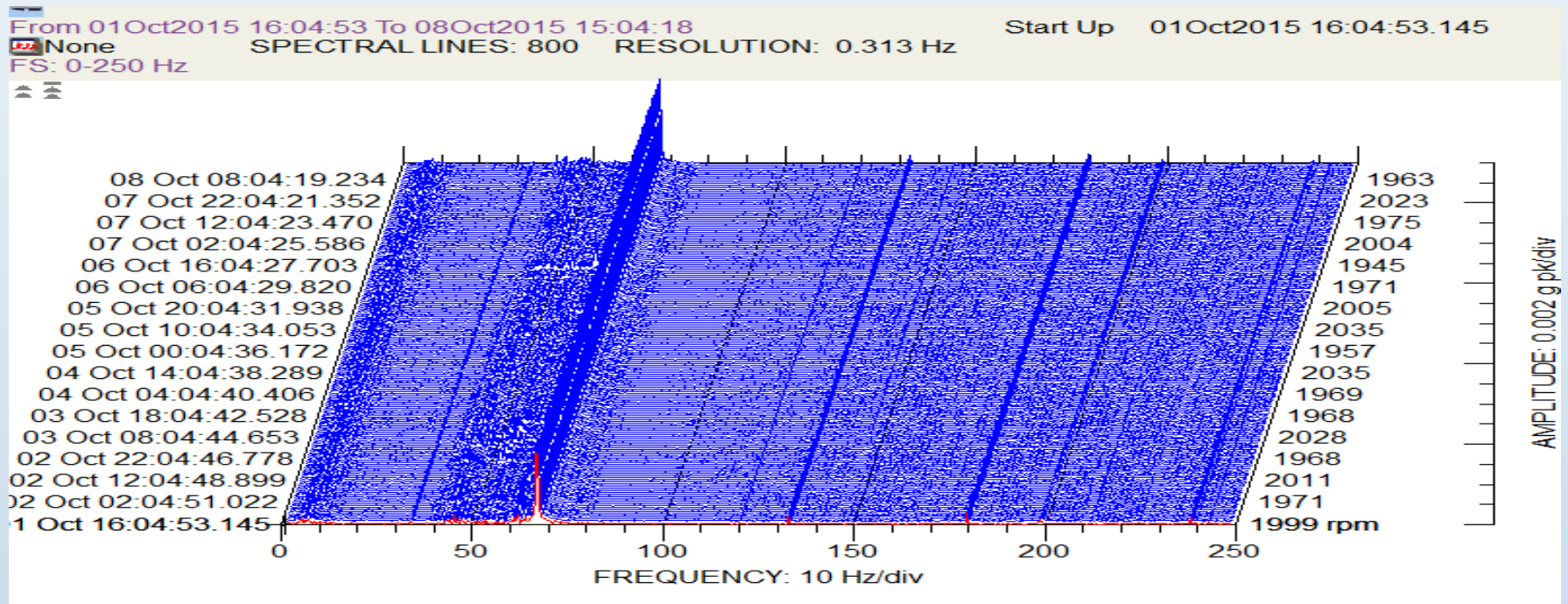
- *Rig accurately duplicates materials, fits, loads, speed, and drive mechanism of flight compressor.*
- *Accelerometers on housings to capture vibration signatures for health monitoring.*
- *Bearing life tests began July 2015 using “discrepant” 60NiTi bearings.*
- *Rig enables evaluation of load effects, speed effects, bearing performance before/after disassembly and re-installation trials.*
- *Tests will run (24/7) until vibration changes or 10,000 hours reached.*



Removable Superelastic Bearings: Experimental Work

Life Tests:

- 4 NiTi bearings currently undergoing 10,000 hour life test.
- 7000+ hours completed
- 1700 and 5000 hour tear-down for visual inspection
 - No damage detected by vibration spectrum, by hand, or visual inspection.





5000 hr: Bearings like new after 600 M cycles





Status and Summary Remarks

- **ISS DA Compressor bearing has been modified to take advantage of the beneficial hardness/superelasticity/corrosion resistance of 60NiTi.**
- **Lower contact stress and increased land heights increase the possibility of reusing compressor bearings after assembly/disassembly process.**
- **Life Testing is underway, with no signs of fatigue failure so far, 7000+ hours completed (10,000 hour target).**
- **Denting tests show that 60NiTi bearings capable of sustaining axial forces up to ~2X removal forces in ISS Compressor application. (SS bearings dented)**
- **Radial loading tests in process. So far, steel bearing damaged, NiTi not damaged.**
- **Successful bearing operation shows that NiTi design parameters (max stress levels, material properties, finishing, etc.) exist to engineer solutions for challenging bearing problems.**



Thank You!



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